

SPECIFICATION

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TOMOSYNTHESIS X-RAY MAMMOGRAM SYSTEM AND METHOD WITH AUTOMATIC DRIVE SYSTEM

Federal Research Statement

The U.S. Government may have certain rights in this invention pursuant to contract number DAMD 17-98-1-8309 awarded by the U.S. Army Medical Research and Materiel Command.

Background of the Invention

- [0001] The present invention relates generally to an imaging system, and more particularly to an X-ray mammogram tomosynthesis system.
- [0002] Conventional X-ray mammography imaging systems utilize an X-ray source mounted on a supporting frame. The frame is manually rotated by the system operator to a place the X-ray source into desired position adjacent to a patient's breast. The X-ray source emits a first shot of X-rays through the patient's breast and an image is captured on a first an X-ray sensitive film positioned on the opposite side of the patient's breast. The frame is then manually rotated into another position by the operator and a second X-ray sensitive film is exposed by a second shot of X-rays. This procedure can be repeated several times to generate several images on different films. The images on the X-ray sensitive films may then be evaluated by a physician and/or digitized and evaluated by a computer. However, such a system produces a two dimensional image of the patient's breast, which provides insufficient information about the presence of tumors and calcification and often leads to false positive readings.

[0003] U.S. Patent No 5,872,828 discloses a tomosynthesis system for breast imaging. This system produces a three dimensional image of the breast being imaged. The tomosynthesis system contains an X-ray source which moves in an arc shaped path over the breast that is being imaged, a stationary digital X-ray detector and an image processor. The detector is mounted on a stationary portion of a support structure. The X-ray source is mounted on a movable portion of the support structure. The movable portion of the support structure is an arm whose lower end is rotatably attached to the stationary support structure at a pivot point, and whose upper end supports the X-ray source.

[0004] However, this tomosynthesis system suffers from several disadvantages. First, the X-ray source is subject to a high amount of vibration because it is mounted to the free, upper end of a rotating arm, while the arm is supported only at the pivot point at its lower end. The vibration of the X-ray source distorts the image. Second, this system requires a high amount of driving power to move the X-ray source. The high driving power is required because torque is applied to the fixed, lower end of the arm, while the heavy X-ray source is mounted to the free, upper end of the arm.

Brief Summary of Invention

[0005] In accordance with one preferred aspect of the present invention, there is an imaging system, comprising an X-ray source adapted to move in an arc shaped path, a stationary electronic X-ray detector, a track, and a mechanical driving mechanism which is adapted to move the X-ray source in the arc shaped path.

[0006] In accordance with another preferred aspect of the present invention there is provided a tomosynthesis X-ray mammography imaging system, comprising an X-ray source adapted to move in an arc shaped path, an arc shaped track provided to allow the X-ray source to move in the arc shaped path, a stationary electronic X-ray detector positioned opposite to the X-ray source, and a mechanical driving mechanism which is adapted to move the X-ray source in the arc shaped path.

[0007] In accordance with another preferred aspect of the present invention, there is provided a tomosynthesis X-ray mammography imaging system, comprising an X-ray source mounted onto an upper portion of a first arm, a second arm having a first side

and a second side and a stationary electronic X-ray detector mounted facing the X-ray source to a first side of the second arm such that an imaging volume is formed above the electronic X-ray detector. The system also comprises a shaft rotatably connecting a middle portion of the first arm to a middle portion of a second side of the second arm, a linear motion track adapted to move relative to the second arm, and a mechanical driving mechanism which is adapted to move a lower portion of the first arm along the linear motion track such that the X-ray source moves in an arc shaped path.

[0008] In accordance with another preferred aspect of the present invention, there is provided a tomosynthesis X-ray mammography imaging system, comprising a first means for irradiating a patient's breast with an X-ray dose at a plurality of steps along an arc shaped path, a second means for mechanically moving the first means in a stepped motion on the arc shaped path around the patient's breast, a third means for detecting the X-rays transmitted through the patient's breast, and a fourth means for constructing a three dimensional image of the patient's breast from a signal output by the third means.

[0009] In accordance with another preferred aspect of the present invention, there is provided a tomosynthesis X-ray imaging method, comprising mechanically moving an X-ray source in a stepped motion on an arc shaped path around an object using a track, irradiating the object with an X-ray dose from the X-ray source located at a plurality of steps along the arc shaped path, detecting the X-rays transmitted through the object with a stationary electronic X-ray detector, and constructing a three dimensional image of the object from a signal output by the electronic X-ray detector.

Brief Description of the Drawings

[0010] Figure 1 is schematic illustration of a system according to the first preferred embodiment of the invention.

[0011] Figure 2 is a side view of a system according to the first preferred embodiment of the invention.

[0012] Figure 3 is schematic illustration of a system according to the second preferred embodiment of the invention.

- [0013] Figure 4 is schematic illustration of a system according to the third preferred embodiment of the invention.
- [0014] Figure 5 is a side view of a system according to the third preferred embodiment of the invention.
- [0015] Figure 6 is schematic illustration of a system according to the fourth preferred embodiment of the invention.
- [0016] Figures 7-9 and 11 are side views of systems according to the fourth preferred embodiment of the invention.
- [0017] Figures 10, 12 and 13 are three dimensional views of systems according to the fourth preferred embodiment of the invention.

Detailed Description of the Invention

- [0018] The present inventors have discovered that X-ray tomosynthesis imaging system speed and accuracy can be improved by using a track and a mechanical drive system which can position an X-ray source at any angle between the vertical to horizontal position on an arc shaped path. The track reduces the vibration of the X-ray source and reduces the driving power required to move the X-ray source.
- [0019] The X-ray source is moved in a stepped motion (i.e., in a sequence of angle increments) about an arc shaped path by the mechanical driving mechanism at a high rate (about 0.1-1.5 seconds per step). The arc shaped path is a path that comprises a portion of a circle or a curved line. While less preferred, the path of the X-ray source may include a full circle, ellipse or polygon. A stationary electronic detector (i.e., an electronic device which detects X-rays, rather than an X-ray sensitive film) is used to detect the X-rays emitted by the X-ray source and attenuated by the imaged object.
- [0020] The imaging system also contains an image processor, such as a general or special purpose computer or a microprocessor chip, such as an ASIC chip. The processor is electrically connected to the electronic detector. The processor forms a three dimensional image of an imaged object from a signal output by the electronic X-ray detector. The processor may use any suitable algorithm to reconstruct a three dimensional image of an imaged object from an arc shaped X-ray source scan. For

example, such an algorithm is disclosed in related U.S. patent application serial number 10/ , (attorney docket number 040849/0186), to Jeffrey Eberhard and Bernhard Claus titled "Generalized Filtered Back-Projection Reconstruction In Digital Tomosynthesis " filed on the same date as the present application and incorporated herein by reference in its entirety. While less preferred, the method disclosed in U.S. Patent No. 5,872,828, incorporated herein by reference in its entirety, may also be used. If desired, the processor may also be used to control the mechanical driving mechanism motion. Alternatively, a separate controller, such as a computer, microprocessor chip or a motor controller, may be used to control the mechanical driving mechanism motion. In this case, the controller is synchronized with the image processor.

[0021] The X-ray imaging system of the preferred embodiments may use any X-ray source, such as an X-ray tube. The X-ray source adapted to move in an arc shaped path is mounted onto a first support. The first support may have many different configurations, as will be described with respect to the preferred embodiments below. In some preferred embodiments the mechanical driving mechanism is adapted to move both the X-ray source and the first support in the arc shaped path. However, in other embodiments, the first support is not moved with the X-ray source.

[0022] Preferably, the electronic detector is mounted to a second support, such as a second support arm, which may be a substantially flat rectangular plate, a cylindrical tube or any other desired shape. An imaging volume is formed between the detector and the X-ray source. For example, an object to be imaged, such as a patient's breast, may be placed on the detector to be imaged and then the X-ray emitting X-ray source is rotated about the object to generate an image. The electronic detector may comprise any detector X-ray detector other than X-ray sensitive film. Preferably, the electronic detector comprises an X-ray sensitive scintillator which emits visible, UV or IR radiation and a solid state radiation detector, such as a silicon charge coupled device or an avalanche photodiode / transistor array, which converts the radiation into an electrical pulse to be sent to the processor. Other detectors, such as photomultipliers and direct X-ray to digital signal detectors, may alternatively be used if desired.

[0023] Preferably, the mammography system is positioned substantially vertical relative to ground (i.e., within 20 degrees of a plane perpendicular to the floor of the building that the system is mounted on), such that a patient standing adjacent to the system may place her breast onto the detector to be imaged. However, the system may also be positioned horizontally to image body parts of patients that are lying down, sitting or in any other desired position between vertical and horizontal. For example, if desired, the entire system may be manually or automatically positioned in any position from vertical to horizontal depending on the desired image.

[0024] The preferred system configurations of the preferred embodiments are described below. However, these configurations are merely illustrative and should not be considered limiting on the scope of the invention. Like part numbers in different figures are used to denote the same element.

[0025] The system 1 of the first preferred embodiment is schematically illustrated in Figure 1. The system 1 includes an X-ray source 3, such as an X-ray tube. The X-ray source 3 is mounted on the first support, which in the first embodiment comprises an arc shaped track 5. The mechanical driving mechanism of the first embodiment comprises a motor 7. The motor 7 is attached to the X-ray source 3 and is adapted to move the X-ray source along the arc shaped track. The motor 7 is also preferably attached to the track 5. The electronic detector 9 is located facing the X-ray source 3 such that an imaging area 11 is formed above the electronic detector 9.

[0026] Figure 2 illustrates a preferred configuration of the system 1 shown in schematic form in Figure 1. The arc shaped track 5 supports the X-ray tube 3. The motor 7 is not shown for clarity. As shown in Figure 2, the detector 9 is mounted on a second support, which is a substantially rectangular, plate shaped arm 13, by fasteners 15, such as brackets, clamps, bolts and/or adhesive. The imaging area 11 optionally contains a breast compression paddle which is used to compress the patient's breast during imaging. The system also has optional handles 17, which may be used to tilt and/or move the system into a desired position. The remaining features on arm 13 shown in Figure 2 comprise structural protrusions, recesses and mounting bolts.

[0027] The system 21 of the second preferred embodiment is schematically illustrated in Figure 3. The system 21 also includes an X-ray source 3, such as an X-ray tube. The

X-ray source 3 is mounted on the first support, which in the second embodiment also comprises an arc shaped track 5. The mechanical driving mechanism of the first embodiment comprises a first arm 27. Preferably, the first arm 27 is made relatively thin and light weight to minimize its mass, but has sufficient rigidity to move the X-ray source 3 along the track 5. The first arm may 27 may comprise a cylindrical or a plate shaped arm which connects the X-ray source 3 to a shaft 29. As shown in Figure 3, the shaft 29 extends in and out of the page. The shaft 29 is turned by a motor or other rotation imparting device (not shown). The step motion of the X-ray source 3 is produced from the shaft 29 torque through the arm 27. The electronic detector 9 is located facing the X-ray source 3 such that an imaging area 11 is formed above the electronic detector 9.

[0028] The magnitude of dynamic forces resulting from the movement of parts in the systems 1 and 21 is linearly proportional to the motion acceleration and the mass in motion. The configurations of the first and second preferred embodiments are advantageous because they minimize the mass in motion. Only the X-ray source 3 alone, or the X-ray source and light weight arm 27 are moving along a track 5. This reduces the required driving power, which in turn allows a use of a motor with a lower weight and size. Since the X-ray source 3 moves along the track 5, its motion is precisely controlled by the track. This reduces the system vibration and improves the image quality. Furthermore, the center of the arc shaped path could be at the detector 9 location (such as in the first embodiment) or at the shaft 29 center (such as in the second embodiment) for optimization of the field of view.

[0029] The system 31 of the third preferred embodiment is schematically illustrated in Figure 4. In the third preferred embodiment, the X-ray source is supported by a rotational arm, which moves along an arc shaped track, rather than being supported by the track as in the first and second embodiment. Thus, the first support for the X-ray source 3 comprises a first arm 37. The arm 37 may have any desired shape, such as a tube or plate shape. The X-ray source 3 is mounted to an upper or first portion of the first arm 37. A lower or second portion of the first arm distal from the first portion is mounted to the arc shaped track 35.

[0030] The mechanical driving mechanism in this embodiment comprises a motor 7. The

motor 7 is adapted to move the lower portion of the first arm 37 along the arc shaped track 35 to move the X-ray source 3 in the arc shaped path. The motor 7 may also be mounted onto the track if desired.

[0031] Figure 5 illustrates a preferred configuration of the system 31 shown in schematic form in Figure 4. With reference to Figures 4 and 5, the detector 9 is mounted to a second support or arm 13, as in the first and second embodiments. A shaft 39 connects the middle portions of the first arm 37 and the second arm 13, such that the arms 13, 37 may rotate relative to each other about the shaft 39 in a scissors-like motion. Preferably, the second arm 13 is stationary while the first arm 37 rotates.

[0032] The electronic detector 9 is mounted to a first or front side of the plate shaped second arm 13, as shown in Figure 5. The detector 9 faces the X-ray source 3 such that an imaging area 11 is formed above the electronic detector 9. The X-ray source 3 is mounted to the first arm 37 such that it is positioned adjacent to the front side of the second arm 13. Thus, the X-ray source 3 moves in the arc shaped path in a plane parallel to the front side of the second arm. However, the first arm 37 itself is preferably positioned adjacent to the second or back side of the second arm 13. A connector (not shown in Figure 5 for clarity) connects the upper portion of the X-ray source 3 to the upper portion of first arm 37, such that the X-ray source 3 and the first arm move on the opposite sides of the second arm 13. Of course different configurations of the arms 13, 37 may be used if desired.

[0033] When the first arm 37 is rotating about the shaft 39, the X-ray source 3 is positioned for angular scans. The rotation torque is created by applying tangential force on the first arm 37 at a radial distance. The bigger the radial distance, the smaller the force is required for the same resultant torque. The lower end of the first arm 37 is the preferred location for the application of the torque because it is the location with the longest radial distance. Therefore, the driving power is minimized when the driving motor 7 is attached at the arm 37 end opposite to the X-ray source 3. The arc shaped track 35 defines the boundary of the first arm 37 motion. Thus, the outline of the moving parts is minimized because no additional moving parts are needed to drive the arm 37.

[0034] A shield or cover (not shown for clarity) is used to close the moving parts for

safety reasons, with the X-rays being emitted through a small slit in the shield. The detector preferably protrudes from the shield. Since the system 31 is compact, the size of shield will be relatively small. This reduces the weight of the system which increases the system's natural frequencies to reduce system vibration.

[0035] The system 41 of the fourth preferred embodiment is schematically illustrated in Figure 6. The system 41 of the fourth preferred embodiment differs from the system 31 of the third preferred embodiment in that a linear motion track rather than an arc shaped track is used. The X-ray source 3 is mounted to an upper or first portion of the first arm 47. The first arm 47 may have any desired shape, such as a tube or plate shape. A lower or second portion of the first arm 47 distal from the first portion is mounted to the linear motion track 45.

[0036] The mechanical driving mechanism in this embodiment comprises a ball screw (not shown in the figures because it is located in the track 45) driven by a motor 7. The ball screw and motor 7 combination is adapted to move the lower portion of the first arm 47 along the track 45, to move the X-ray source 3 in the arc shaped path. The motor 7 may also be mounted onto the track if desired. A side pin 43 is positioned to create a stable whole range drive by allowing the track to rotate with respect to a fixed point.

[0037] Figure 7 illustrates a preferred configuration of the system 41 shown in schematic form in Figure 6. With reference to Figures 6 and 7, the detector 9 is mounted to a second support or arm 13, as in the first through third embodiments. A shaft 49 connects the middle portions of the first arm 47 and the second arm 13, such that the arms 13, 47 may rotate relative to each other about the shaft 49 in a scissors-like motion. Preferably, the second arm 13 is stationary while the first arm 47 rotates.

[0038] In a preferred embodiment of the fourth embodiment, a pivot point plate 44 is attached to the second arm 13, as shown in Figure 7. The pivot point plate 44 is rotatably mounted to the linear motion track 45 by the side pin 43. The pivot plate 44 and track 45 optionally have holes 46 which reduce the weight of the plate 44 and track 45.

[0039] Figures 8 and 9 illustrate the method of operation of the system 41 of the fourth

preferred embodiment. The X-ray source 3 is mounted to the first arm 47 such that it is positioned adjacent to the front side of the second arm 13. Thus, the X-ray source 3 moves in the arc shaped path in a plane parallel to the front side of the second arm. However, the first arm 47 itself is preferably positioned adjacent to the second or side of the second arm 13. A connector (not shown in Figures 8 and 9 for clarity) connects the upper portion of the X-ray source 3 to the upper portion of first arm 47, such that the X-ray source 3 and the first arm 47 may be moved past the second arm 13 on the opposite sides of arm 13. Of course different configurations of the arms 13, 47 may be used if desired.

[0040] The relative rotational movement of pivot plate 44 and track 45 around pin 43 allows movement of the first arm 13 relative to track 45. Preferably, the second arm 13 supporting the detector 9 remains stationary while the track 45 moves relative to the second arm. The first arm 47 and the second arm 13 are rotatably connected by shaft 49. The movement of the track 45 relative to second arm 13 allows translation of the linear motion of the lower portion of the first arm 47 along track 45 into arc shaped motion of the X-ray source 3 mounted to the upper portion of the first arm 47, as shown in Figures 8 and 9. The X-ray source 3 moves from a right side position in Figure 8 along the arc shaped path into a left side position relative to the second arm 13 in Figure 9. At the same time, the track 45 moves from a first position in Figure 8 to a second position in Figure 9 relative to the second arm 13, while the lower portion of the first arm 47 moves from left in Figure 8 to right in Figure 9 to achieve the arc shaped path of the X-ray source 3. Thus, the track 45 moves vertically relative to the shaft 49 during movement of the first arm 47 to translate linear motion along track 45 into arc shaped motion.

[0041] Figure 10 is a three dimensional illustration of system 41 of the fourth preferred embodiment. Figure 10 shows the connector 48 which connects the second arm 47 and the X-ray source 3. The connector 48 extends over the second arm 13 and allows the first arm 47 and the X-ray source 3 to move on opposite sides of the second arm 13.

[0042] Figures 11 and 12 illustrate an alternative aspect of the system of the fourth preferred embodiment. In this aspect, the pivot plate 44 is omitted from the system

51. Instead, the second arm 13 is mounted to the track 45 by a movable member 53 and pin 43. The movable member allows relative vertical motion between the second arm 13 and the track 45. For example, the movable member 53 may be a piston which is rotatably mounted to the track 45 by pin 43, and which extends and retracts in a direction perpendicular to the track 45 to allow the relative movement between the secondary arm 13 and the track 45. This motion allows the X-ray source 3 to move in the arc shaped path. The first arm 47 is connected to the track 45 by a pin 55 which allows rotational movement of arm 47 relative to track 45 as well as linear motion of arm 47 along the track 45.

[0043] Figure 13 illustrates the system 41 of the fourth preferred embodiment mounted to a gantry or base 57. The right side of Figure 13 shows a close up of the first arm 47 and the second arm 13, while the left side of Figure 13 shows a close up of the electronic detector 9. The detector 9 is mounted over the gantry 57 in a position which allows a patient to place her breast onto the detector 9. The system 41 may be adjustable in the vertical direction relative to the ground to allow patients of different height to use the system without stretching or bending. The compression paddle 58 is likewise height adjustable. The preferred electronic detector 9 contains an amorphous silicon photodetector array 61 formed on a glass substrate 59. The array 61 includes metal contact fingers 63 and metal contact leads 65. An X-ray sensitive scintillator material 67 is formed over the array 61. The scintillator material 67 emits radiation having a wavelength detectable by the silicon pixels in the array 61 in response to receiving an X-ray. The magnitude of the radiation is proportional to the attenuation of the X-rays by the imaged object. The pixels of array 61 converts the received radiation into an electrical signal of a predetermined magnitude that is provided to the processor and then converted into an image by the processor.

[0044] It should be noted that "upper" and "lower" refers to directions in a preferred vertically mounted system. These directions would differ in a non-vertically mounted system of other aspects of the present invention. The mechanical driving system of the preferred embodiments requires low driving power, provides a low amount of system vibration, and a small outline of moving part boundary to reduce the size of the system. The X-ray tomosynthesis imaging system with the track, the mechanical drive and electronic detector is especially advantageous for mammography because it

forms an accurate three dimensional image of the breast in a short amount of time and provides an improved image contrast adjacent to the skin of the breast. However, the imaging system may be used to image other parts of a patient's body as well as animals and inanimate objects, if desired.

[0045] As discussed above, the systems of the preferred embodiments of the present invention are preferably used in a tomosynthesis X-ray mammography imaging method. However, other patient body parts, animals and/or inanimate objects may also be imaged if desired. The preferred mammography method includes mechanically moving the X-ray source 3 in a stepped motion on an arc shaped path around a patient's breast and irradiating the patient's breast with an X-ray dose from the X-ray source located at a plurality of steps along the arc shaped path. The X-rays transmitted through the patient's breast are then detected with the electronic X-ray detector 9 and a three dimensional image of the patient's breast is constructed from a signal output by the electronic X-ray detector 9. Preferably, the detector 9 is arranged at the gantry 57 such that the patient is standing adjacent to the machine and the patient's breast is located on the electronic X-ray detector 9, while the X-ray source 3 moves above the patient's breast in the arc shaped path.

[0046] In the first preferred embodiment, the step of mechanically moving an X-ray source comprising moving the X-ray source 3 on the arc shaped track 5. In the second preferred embodiment, the X-ray source 3 is moved on the arc shaped track 5 by a first arm 27 being rotated by a motor. In the third preferred embodiment, the step of mechanically moving an X-ray source 3 comprises moving a first portion of a first arm 37 on the arc shaped track 35 while a second portion of the first arm 37 supports the X-ray source 3. In the fourth preferred embodiment, the step of mechanically moving an X-ray source comprises moving the first arm 47 supporting the X-ray source 3 on a linear motion track 45 while allowing relative motion between the track 45 and a second arm 13 supporting the electronic X-ray detector 9.

[0047] The method of the preferred embodiments of the present invention is advantageous because it allows for a fast scan of the imaged object. For example, 10 projections can be taken in about 1 to 15 seconds, such as 3 to 10 seconds, preferably 3 to 5 seconds. Thus, the X-ray source takes between 0.1 to 1.5 seconds

between projection positions, such as 0.1 to 0.5 seconds or 0.3 to 1 seconds, preferably 0.3 to 0.5 seconds. The X-ray source 3 is capable of traveling an arc shaped path of 50 or more degrees, such as about 20 to 60, preferably 30 to 50 degrees, such that the arc shaped path contains 5 to 15 steps separated by about 2 to about 10 degrees. The X-ray source emits a dose of X-rays at each step. This provides for a fast patient throughput while maintaining accurate, repeatable, customizable, automated X-ray source motion. Furthermore, the electronic detector 9, such as a digital detector, is capable of handling multiple exposures per second, in contrast to conventional X-ray film.

[0048] The preferred embodiments have been set forth herein for the purpose of illustration. However, this description should not be deemed to be a limitation on the scope of the invention. Accordingly, various modifications, adaptations, and alternatives may occur to one skilled in the art without departing from the scope of the claimed inventive concept.